

Web Application for Modeling Global Antineutrinos

A.M. Barna

CASPO, Scripps Institution of Oceanography, La Jolla, CA 92093 USA

S.T. Dye

*Department of Physics and Astronomy, University of Hawaii, Honolulu, HI, 96822 USA and
Department of Natural Sciences, Hawaii Pacific University, Kaneohe, HI, 96744 USA*

(Dated: October 20, 2015)

Electron antineutrinos stream freely from rapidly decaying fission products within nuclear reactors and from long-lived radioactivity within Earth. Those with energy greater than 1.8 MeV are regularly observed by several kiloton-scale underground detectors. These observations estimate the amount of terrestrial radiogenic heating, monitor the operation of nuclear reactors, and measure the fundamental properties of neutrinos. The analysis of antineutrino observations at operating detectors or the planning of projects with new detectors requires information on the expected signal and background rates. We present a web application for modeling global antineutrino energy spectra and detection rates for any surface location. Antineutrino sources include all registered nuclear reactors as well as the crust and mantle of Earth. Visitors to the website may model the location and power of a hypothetical nuclear reactor, copy energy spectra, and analyze the significance of a selected signal relative to background.

I. INTRODUCTION

The flux and energy spectrum of electron antineutrinos from β^- decay measured at the surface of Earth provides important information on the location and operation of nuclear reactors, the quantity and distribution of planetary radioactivity, and the mass states of neutrinos. The monitoring of antineutrinos from nuclear reactors at long [1, 2] and short [3, 4] distances has important applications for nuclear non-proliferation [5], as well as significant capabilities for fundamental physics [6–8]. Knowledge of the reactor antineutrino flux is essential for the observation of geological antineutrinos [9]. Geo-neutrino observations apprise terrestrial radiogenic heating [10, 11], guiding basic understanding of the composition, structure, and thermal evolution of Earth [12]. Recent modeling projects provide static maps the surface flux of antineutrinos [13, 14] with planned revisions and additions as the inventory of nuclear reactors changes, geo-neutrino observational exposures increase, and geological modeling becomes more sophisticated. The web application, described herein and available at <http://geoneutrinos.org/reactors>, complements the mapping projects by estimating and displaying the energy spectrum and detection rate of electron antineutrinos at any surface location. This dynamic display allows users to download energy spectra and to analyze the significance of a selected signal relative to background, providing an estimate of the required detector exposure.

II. REACTOR ANTINEUTRINOS

Nuclear power reactors are intense sources of antineutrinos, which emerge during the beta decay of short-lived fission products. An empirical fit estimates the energy

spectrum of un-oscillated electron antineutrinos detected at a distance R (km) from a reactor with a thermal power P (GW) with the formula

$$N(E_{\bar{\nu}_e}) = 2075(E_{\bar{\nu}_e} - e_2)^2 \exp\left[-\left(\frac{E_{\bar{\nu}_e} + e_1}{e_3}\right)^2\right] \frac{P}{R^2}, \quad (1)$$

which is valid for $E_{\bar{\nu}_e}$ greater than the inverse beta decay interaction threshold energy. The values of the parameters are $e_1 = 0.8$, $e_2 = 1.43$, and $e_3 = 3.2$ all in units of MeV. In (1), the decaying exponential describes antineutrino production and the rising quadratic represents the interaction cross section.

Mixing of neutrino mass states along the flight path from source to detector converts some of the electron antineutrinos to a flavor (μ , τ) that does not participate in the inverse beta decay interaction at MeV-scale energy. This flavor oscillation suppresses the detection rate and introduces conspicuous features to the energy spectrum. With three active neutrinos the survival probability is

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \cos^4 \theta_{13} \sin^2(2\theta_{12}) \sin^2(\Delta_{21}L/E_{\bar{\nu}_e}) - \sin^2(2\theta_{13}) \cos^2 \theta_{12} \sin^2(\Delta_{31}L/E_{\bar{\nu}_e}) - \sin^2(2\theta_{13}) \sin^2 \theta_{12} \sin^2(\Delta_{32}L/E_{\bar{\nu}_e}), \quad (2)$$

where $\Delta_{ij} = 1.27\delta m_{ij}^2$, L is in meters, and $E_{\bar{\nu}_e}$ is in MeV. Using the identities $\delta m_{31}^2 = \delta m_{21}^2 + \delta m_{32}^2$, $\cos^2 u = 1 - \sin^2 u$, and $\sin(2u) = 2 \sin u \cos u$, (2) is determined by the values $\delta m_{31}^2 = (2.457 \pm 0.047) \times 10^{-3} \text{ eV}^2$, $\delta m_{21}^2 = (7.50 \pm 0.19) \times 10^{-3} \text{ eV}^2$, $\sin^2 \theta_{12} = 0.304 \pm 0.013$, [15] and $\sin^2 \theta_{13} = 0.0215 \pm 0.0013$ [16]. The given value of δm_{31}^2 applies to normal mass hierarchy. Inverted mass hierarchy is approximated by using $\delta m_{32}^2 = (2.457 \pm 0.047) \times 10^{-3} \text{ eV}^2$ and $\delta m_{32}^2 = \delta m_{21}^2 + \delta m_{31}^2$.

III. GEO-NEUTRINOS

The sources of antineutrinos from Earth are assumed to be crust and mantle. These geological reservoirs of the silicate portion of Earth contain thorium and uranium [17], which through a series of decays transmute to stable isotopes of lead. Several beta decay spectra in these series have endpoint energy greater than the 1.8 MeV detection threshold energy, providing an observable geo-neutrino signal [18]. The probability density distributions as a function of energy for uranium and thorium geo-neutrino interactions are calculated and displayed in Figure 1. Due to the different shapes of the distributions a geological reservoir with a given ratio of thorium to uranium produces a geo-neutrino interaction spectrum characteristic of the given ratio. Geo-neutrino observations to date lack sufficient exposure to measure the thorium to uranium ratio of the recorded interactions.

The surface geo-neutrino signal is observed with significance by two underground detectors, one in Japan [10] and one in Italy [11]. Although geological models of the crust predict distinct variation in the surface geo-neutrino signal [19], the observed signals are consistent with each other. It remains the task of future observations, perhaps with detectors at locations informed by this web application, to independently test this fundamental geological model.

The web application displays at each Earth surface location the energy spectrum and detection rate of geo-neutrinos. The contribution from the crust is calculated from a model prediction of the non-oscillated geo-neutrino fluxes from thorium and uranium [19]. Fluxes are converted to detection rates using standard methods [18]. An average survival probability, given by

$$\overline{P}_{\nu_e \rightarrow \bar{\nu}_e} = \frac{1}{2} \cos^4 \theta_{13} (1 - \sin^2(2\theta_{12})) + \sin^4 \theta_{13}, \quad (3)$$

accounts for the effects of neutrino oscillations. A constant suppression factor of 0.55 follows from the identities and values given in the previous section. Due to uncertainties in the model-dependent predictions for the mantle geo-neutrino rate and spectrum, these quantities are specified by the user of the web application.

IV. SIGNAL SIGNIFICANCE

An important function of this web application is the assessment of the significance of observing a signal in the presence of background. The assessment statistic is

$$N\sigma = \frac{S\sqrt{t}}{\sqrt{S+2B}}, \quad (4)$$

with S the signal, B the background, and t the dwell time. With S and B in TNU, t is given in years of exposure of a perfect detector with 10^{32} free proton targets. Presently, the web application does not include

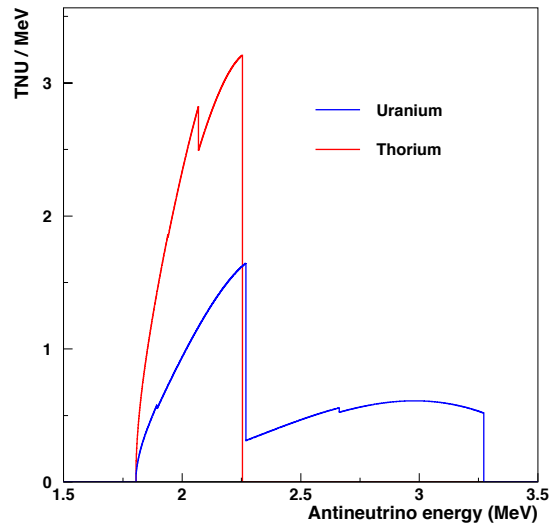


FIG. 1. Probability density distributions, normalized to 1 event from a perfect exposure of 10^{32} free protons for 1 year (1 TNU), for thorium and uranium geo-neutrino interactions.

background due to cosmogenic sources or accidental coincidences.

V. WEB APPLICATION

The web application consists of four pages: "Detector," "Reactors," "GeoNu," and "Output & Stats." Each page has a pane displaying a Mercator projection of Earth. On the map, land areas are shown in tan with country borders in thin black lines and water areas are shown in blue.

The "Detector" page has two additional panes: "Spectrum" and "Location." The "Spectrum" pane shows the energy spectrum of electron antineutrino detection rates, some output text on rates and distances, and the "Invert Neutrino Mass Hierarchy" checkbox. The spectrum plot displays the total of all rates (black line), the contribution from all IAEA-registered reactors (shaded green), the contribution from the closest reactor core (shaded gray), the contribution from geo-neutrinos (shaded yellow), the contribution from uranium geo-neutrinos (blue line), and the contribution from thorium geo-neutrinos (red line). The "Location" pane has boxes showing the detector "Latitude" and "Longitude" values, the "Follow Cursor On Map" checkbox, and the "Location Presets" box.

The "Reactors" page has two additional panes: "Reactor Load Factors" and "Custom Reactor." The "Reactor Load Factors" pane simply contains the box for selecting either "Mean LF" or "2013 LF." The "Custom Reactor" pane has the "Power" box for setting the thermal power of the custom reactor, the "Use Custom Reactor" checkbox, and the "Location" sub-pane with boxes showing

the custom reactor "Latitude" and "Longitude" values and the "Place Reactor" button.

The "GeoNu" page has two additional panes: "Mantle" and "Crust." The "Mantle" pane has the "Mantle Signal" box for setting the interaction rate in TNU and the "Th/U Ratio" box for setting the spectral shape of the mantle signal. The "Crust" pane simple displays some text, referencing the source of the crust flux values.

The "Output & Stats" page has the additional "Calculator" pane and an untitled output data box for inspecting, or copying, the plotted energy spectrum values. The "Calculator" pane has the "Signal" box for selecting the source with background of the antineutrino signal, the "Solve For" box for selecting whether the calculation returns the "Exposure Time" or the "Significance," the " E_{min} " box for setting a lower energy cut (in MeV) on the spectrum to be analyzed, the " E_{max} " box for setting the upper energy cuts (in MeV) on the spectrum to be analyzed, the "Time (years)" box for setting the exposure time if the "Solve For" box is set to "Significance," and the "Sigma" box or setting the significance if the "Solve For" box is set to "Exposure Time." The untitled output data box contains the antineutrino rate energy spectrum and its components at the selected location. The data, which range from 0 to 10 MeV, are in units of TNU per 10 keV. There are six columns of data separated by commas, which correspond to: total rate, rate from all known IAEA reactor cores, rate from closest reactor core, rate from user-defined core (0 if not using a custom reactor), rate from uranium geo-neutrinos, and rate from thorium geo-neutrinos. There are a total of 1000 rows of data under each column. The first 180 data rows have value 0 due to the 1.8 MeV energy threshold of the electron antineutrino inverse beta decay interaction on a free proton. For plotting or further analysis, users simply copy and paste the contents of this box into a text file or spreadsheet program.

A. Development Framework

Our web application is built using Flask [20], a micro-framework written in Python [21]. Flask is utilized for Uniform Resource Locator (URL) routing and rendering web page templates. Only calculations required to route and render templates are performed on the web server. The computations for rendering the user interface, output figures, and output text data are handled by the client-side web browser. All client-side programs are written in JavaScript (ECMAScript 5.1). The components of the client-side programs are described in this section.

B. Request Routing

When the client-side web browser requests data from a web server using Hypertext Transfer Protocol (HTTP), the server needs to determine the response. While some web server software is configured with a set of rules to determine what, if anything, should be returned to the requesting agent, Flask uses a routing table. The routing table contains a list of routes (e.g. /model) and the call methods of the routes. Query parameters and URL fragments are ignored when determining a matching route.

The call method returns a suitable response, usually some text body and appropriate HTTP header fields. This can be as simple as returning a preset string or as complicated as performing a set of complex calculations to generate the response. Most of the methods employed by our web application simply compose and return web page templates. Irrespective of purpose, it is important for the response time to be fast, usually less than one second.

C. Web Page Template Rendering

A templating system minimizes code repetition and speeds development. Specifically, we use jinja2 [22]. A base template is defined (see: webnu/templates/base.html in the source), which contains basic elements displayed on all pages. This would include the Hypertext Markup Language (HTML) headers, the navigation bar appearing on every page, the JavaScript script, and the web style sheets, which are used by all pages. The base page template includes several placeholders where content from other page templates can be placed.

Other page templates are inherent and extend the base page template. When, for example, the /reactors page is requested, the reactor page template is found and starts to be rendered. The reactor page template has a declaration to extend the base page template in it and contains only the content for the placeholders in the base page template. This content is then placed inside the placeholders and the entire result is returned to the user.

D. Rendering a Page

The events, which occur when the reactors page is requested, are as follows (in this order):

1. The page template is rendered and returned.
2. When the returned HTML element is parsed, the browser starts rendering the page.
3. When the links to style sheets are encountered, the rendering is blocked until the style sheets are fetched.

4. References to external JavaScript files are loaded in the order they appear in the document.
5. The reactor data is loaded as part of these external files.
6. Since the main application JavaScript is inline and at the bottom of the document, it executes as soon as it is encountered.
7. The spectrum plot is initialized (though empty) and the methods used to dispatch events (event listeners) are attached to elements on the webpage.
8. The method for updating the spectrum plot is called once for the default display.

Once the above has finished, the page is ready for user input and will wait for an event needing a response.

E. User Input Events

The interaction between the browser rendered document and any JavaScript is usually by what are called Events. Events are fired automatically by the web browser when the user performs certain actions. The reactor page is listening for the following events:

- The cursor has moved while over the map.
- The cursor has clicked the map.
- The Detector latitude has changed.
- The Detector longitude has changed.
- The Follow Cursor On Map checkbox has changed.
- The Detector preset selection has changed.
- The Reactor power has changed.
- The Use Custom Reactor checkbox has changed.
- The Custom Reactor latitude has changed.
- The Custom Reactor longitude has changed.
- The Place Reactor button has been clicked.
- The Invert Neutrino Mass Hierarchy checkbox has changed.

Each of these events can cause a state change in the application. The events may also be in conflict with each other, prompting a brief discussion of how each event is handled.

1. Cursor Move Over Map

An event listener for the JavaScript mouse-move is attached to the map image. When the cursor (mouse) moves while over the map, the attached function is called with the Event passed into it. If the Follow Cursor On Map checkbox is selected, the coordinates from the event are translated into latitude and longitude. The latitude and longitude values are placed in the appropriate box in the detector Location panel. The Location Presets selection input is set to no selection. Finally the update spectrum function is called.

If the Follow Cursor On Map checkbox is not selected, the function returns immediately without doing anything.

2. Cursor Click on Map

The JavaScript click event is listened for on the map. When clicked, usually the Follow Cursor On Map checkbox is toggled. The exception is if the user has clicked the Place Reactor button. If this is the case, the next click will set the latitude and longitude of the custom reactor.

3. Text Input of Checkbox Change

When any of the text input boxes has a value change, the update spectrum routine is simply called. These boxes include the reactor power box, the reactor latitude and longitude boxes, and the detector latitude and longitude boxes. If the state of either the Invert Neutrino Mass Hierarchy or the Use Custom Reactor checkbox has changed, the update spectrum routine is called.

4. Preset Selected

When the user selects an option from the Location Presets selection input the latitude and longitude for that detector are placed in the text inputs. The Follow Cursor On Map checkbox is set to off. The update spectrum function is then called.

F. Spectrum Update

Most user actions require an updated energy spectrum, making the spectrum update function central to the web application. The function has several important tasks:

- Get the new user input values;
- Calculate the distances to the detector from all the reactors;

- Calculate the neutrino oscillation survival probability distribution for each distance;
- Multiply the reactor output spectrum by the appropriate survival probability distribution;
- Sum all the oscillated reactor output spectra;
- Draw the new spectrum plot;
- Locate the detector and reactor icons on the map;
- Update the spectrum text output.

When the spectrum update function is called it performs the following actions. First, the detector and user reactor icon locations are set. To do this, the latitude and longitude of the detector and user reactor are taken directly from the text input fields on the webpage. Then the geographic coordinates are converted to the image coordinates of the map with the origin in the upper left corner. The detector and user reactor image positions are then set with the image coordinates. If the user does not want the custom reactor to be used, the reactor image display attribute is set to none.

Next the distance and spectral contribution of each reactor are calculated. For computational simplicity, reactor positions are stored as Cartesian coordinates in a three dimensional array. The distance between each reactor and the user provided detector location is given by the Euclidean distance. The neutrino spectrum function is called for each reactor, the returning spectra are stored separately temporarily. The distance loop records which reactor is the closest to the detector so its contribution may be plotted separately on the output figure.

The spectrum update function then calculates all the ancillary output parameters: the distances to the user reactor and the closest reactor, and the TNU outputs. It also updates the text spectrum output box.

Finally, the line plot figure is updated. Since the D3.js [23] data binding library is used, this is done simply by instructing D3 to use the newly calculated values. The y-axis domain is updated. The entire figure does not need to be redrawn, only what has changed.

G. Survival Probability

The neutrino oscillation survival probability function calculates the probability distribution spectrum for an input distance. Due to multiple calls to computationally expensive trigonometric functions specified by (2), the computed spectrum for any given input distance is cached for future use.

H. Additional Calculation

The resulting signal components are cached for additional analysis provided by the "Calculator" pane. On

the Calculator pane, we provide the ability to calculate the exposure time required to have a user input signal significance or the signal significance provided by a given exposure time. The additional analysis does not require recalculation of the component signals so the results are nearly instantaneous. The calculator pane is implemented as an independent "web app" which only has the results of the reactor, and geo-neutrino calculations as the input.

VI. DISCUSSION

We demonstrate this web application with several examples relevant to nuclear non-proliferation and observational neutrino geoscience. Readers who visit <http://geoneutrinos.org/reactors> can follow along.

Detecting the diversion from the reactor core of a significant quantity of material (e.g. 8 kg Pu), which could be directly used in manufacturing a nuclear explosive device, with a high probability ($> 95\%$) within 30 days is an established nuclear safeguard [24]. The capability of meeting the criteria of this safeguard by the observation of reactor antineutrinos is an area of active research. Electron antineutrino detectors of cubic meter size are capable of monitoring the operation of nuclear reactors when deployed about 10 meters from the reactor core and at a depth equivalent only to about 10 meters of water. Successful demonstrations include the monitoring of both 3-GW commercial [4] and 70-MW research [3] reactors. Demonstrations at greater distances require larger detectors, probably operating under greater overburden.

A nuclear monitoring demonstration project under discussion [25] involves deploying a 1000 cubic meter detector 13 km from the Perry Nuclear Power Plant east of Cleveland, Ohio and in a salt mine at a depth equivalent to about 1.5 km of water. An existing excavation in the mine, which formerly housed the IMB nucleon decay detector [26], would accommodate the nuclear monitoring demonstration detector. The rate and energy spectrum of antineutrinos estimated by this web application for this site is displayed by selecting "IMB" under the "North America" category in the "Location Presets" box in the "Location" pane of the "Detector" page. The total rate is dominated by the closest core (94 – 95%, depending on the load factor), which is 13 km away. Moving to the "Output & Stats" and selecting "Closest Core (geonu + other reactors background)" in the "Signal" box in the "Calculator" pane shows that a 3σ detection would result from a perfect detector of 10^{32} free proton targets exposed for 0.15% of a year, which is about 13 hours. This level of significance would take the nuclear monitoring demonstration detector a considerably longer time to achieve due to a smaller number of targets, a less than perfect detection efficiency primarily due to relying solely on Cherenkov light for the detectable signal, and cosmogenic background, which is presently not accounted for by the web application. However, the exposure time would

still be much less than the 30 days established by the IAEA safeguard.

While 13 km is much farther than the ~ 10 meter distances demonstrated by the meter cube projects, it is still closer than 100 km, which is considered by the intelligence community to be the distance beyond which remote monitoring occurs. In our second example, enter latitude 34.75 N and longitude -121.89 E in the "Location" pane of the "Detector" page. This places a detector 107 km offshore from the Diablo Canyon Nuclear Plant at San Luis Obispo, CA. and near the Santa Lucia Escarpment in 3.6 km of water. The energy spectrum plot shows the closest core contributes 42 – 43% of the total rate. The reduction compared with the previous example is because the Diablo Canyon Nuclear Power Plant has two reactor cores rather than the single core at the Perry Nuclear Power Plant. Note the wiggled structure in the spectrum due to neutrino oscillations, in particular the prominent dip at about 2.3 MeV. Shifting to the "Output & Stats" page shows that a 3σ detection would result from a perfect detector of 10^{32} free proton targets exposed for about 45% of a year, which is about 163 days. Cutting off the energy spectrum below 2.3 MeV removes more background than signal, thereby reducing the exposure time to about 41% of a year, which is about 150 days. Decreasing this exposure time to the 30 day safeguard level could be accomplished by increasing the size of the detector to greater than 5×10^{32} free proton targets. Cosmogenic background would be significantly reduced by the deep ocean water compared with the relatively shallow salt mine site in the previous example. Moreover, if scintillating liquid (oil- or water-based) were used instead of water, the detection efficiency could be $> 80\%$ [10, 11]. The feasibility of deploying an electron antineutrino observatory in the deep ocean is addressed by a previous study [27]. This example indicates that remote monitoring of nuclear reactor operation is a realistic possibility off the coast of California.

One goal of nuclear monitoring is the discovery of a clandestine reactor. The web application aids in specifying the observational requirements to make such a discovery. The following example is considerably contrived and fully hypothetical. Nonetheless it serves to illustrate the function of the web application. Use the same detector location as in the previous example (34.75 N and -121.89 E). In the "Reactors" page set the "Use Custom Reactor" checkbox and dial up the "Power" box to 40 MW. In the "Location" sub-pane enter "Latitude" 34.98 N and "Longitude" -121.37 E. This places a custom reactor 54 km from the detector on a line directly to the Diablo Canyon Nuclear Power Plant. The energy spectrum plot on the "Detector" page shows the rate from the closest reactor is only about 1% of the total rate. Selecting "Closest Core (geonu + other reactors background)" in the "Signal" box of the "Calculator" pane on the "Output & Stats" page with the "Solve For" box set to "Exposure Time" finds that 836 years of exposure of a perfect detector with 10^{32} free proton targets is required

for a 3σ detection. A very rough estimate of the exposure is 1000 TNU^{-1} . If the positive detection is required in N years, then the detector size is given by $1000/N \times 10^{32}$ free protons. A positive detection in five years would require a detector of about 250 kT of scintillating liquid. The largest scintillating liquid antineutrino detector under discussion tips the scales at 50 kT [28], making the present example within the realm of possibility.

As a final example, this one relevant to neutrino geoscience, select "ACO" under the "Pacific Ocean" category in the "Location Presets" box in the "Location" pane of the "Detector" page. This places a detector at the Aloha Cabled Observatory [29] site 100 km north of Oahu, Hawaii. With the closest reactor over 3500 km distant the energy spectrum plot clearly shows that the estimated signal is dominated by geo-neutrinos. Moreover, about one-half of the total estimated signal originates in the mantle. Moving to the "Output & Stats" and selecting "Geoneutrino (reactor background)" in the "Signal" box in the "Calculator" pane shows that a 3σ detection would result from a perfect detector of 10^{32} free proton targets exposed for 1.19% years. At a depth of almost 5 km cosmogenic background would be negligible. This example reinforces the previously stated conclusion that the measurement of mantle geo-neutrinos is greatly facilitated by observation from the deep ocean [30–33].

VII. REVISIONS AND ADDITIONS

As with the static mapping projects [13, 14] revisions and additions can be implemented to improve this web application. Perhaps the most prominent deficiency is the omission of uncertainties in the modeled antineutrino rates. Although these uncertainties are relatively small ($< 5\%$) for the rate from a reactor of known power output, uncertainties associated with the geological antineutrino rates are large ($\sim 20\%$ for the crust and $> 50\%$ for the mantle). Including information on the uncertainties in the modeled rates would be useful. There remains a very interesting possibility of enhanced geo-neutrino emission from two seismically resolved large structures at the base of the mantle [34], the so-called large low-seismic velocity provinces (LLSVPs). Incorporating the seismic models and the ability to specify radiogenic element concentrations within a volume bounded by a certain seismic speed deficit would allow calculation of corresponding surface rate enhancement. As the capability to resolve the direction of antineutrino signals develops the angular distribution of sources at a given detection site becomes beneficial. Adding the means to plot anisotropic crust, reactor, and LLSVP distributions to the web application would be helpful. Modeling of radiogenic element concentrations in continental crust is maturing and refinements seem inevitable. Besides improving the estimate of the crust rate, potential revisions include upgrading the geo-neutrino and reactor spectra with those resulting from more precise calculations.

VIII. CONCLUSIONS

We present a web application for modeling global antineutrino energy spectra and detection rates for any surface location. Sources include all registered nuclear reactors as well as the crust and mantle of Earth. Visitors to the website may model the location and power of a hypothetical nuclear reactor, copy energy spectra, and analyze the significance of a selected signal relative to background.

ACKNOWLEDGMENTS

This work was supported in part by the Lawrence Livermore National Laboratory. The authors thank W.F. McDonough for providing the crust flux model in a useful format, G.R. Jocher for furnishing a listing of registered nuclear reactor information, and A. Bernstein for useful comments and suggestions during the development of the web application.

-
- [1] G. R. Jocher *et al.*, “Theoretical antineutrino detection, direction, and ranging at long distances,” *Phys. Rep.* **527**, 131 (2013).
 - [2] T. Lasserre *et al.*, “SNIF: A Futuristic Neutrino Probe for Undeclared Nuclear Fission Reactors,” arXiv:1011.3850 (2010).
 - [3] G. Boireau *et al.*, “Online Monitoring of the Osiris Reactor with the Nucifer Neutrino Detector,” arXiv:1509.05610 (2015).
 - [4] N. S. Bowden *et al.*, “Experimental Results from an Antineutrino Detector for Cooperative Monitoring of Nuclear Reactors,” *Nucl. Inst. Meth.* **A572**, 985 (2007).
 - [5] A. Bernstein *et al.*, “Nuclear Security Applications of Antineutrino Detectors: Current Capabilities and Future Prospects,” *Sci. Glob. Sec.* **18**, 127 (2010).
 - [6] R. F. and C. L. Cowan, “Detection of the free neutrino,” *Phys. Rev.* **92**, 830 (1953).
 - [7] F. Reines, H. S. Gurr, and H. W. Sobel, “Detection of $\bar{\nu}_e - e$ scattering,” *Phys. Rev. Lett.* **37**, 315 (1976).
 - [8] J. G. Learned *et al.*, “Determination of Neutrino Mass Hierarchy and θ_{13} with a Remote Detector of Reactor Antineutrinos,” *Phys. Rev.* **D78**, 071302 (2008).
 - [9] T. Araki *et al.*, “Experimental investigation of geologically produced antineutrinos with KamLAND,” *Nature* **436**, 499 (2005).
 - [10] A. Gando *et al.*, “Reactor on-off antineutrino measurement with KamLAND,” *Phys. Rev. D* **88**, 033001 (2013).
 - [11] M. Agostini *et al.*, “Spectroscopy of geo-neutrinos from 2056 days of Borexino data,” *Phys. Rev.* **D92**, 031101 (2015).
 - [12] S. T. Dye *et al.*, “Geo-neutrinos and Earth models,” *Phys. Proc.* **61**, 310 (2015).
 - [13] M. Baldoncini *et al.*, “Reference worldwide model for antineutrinos from reactors,” *Phys. Rev.* **D91**, 065002 (2015).
 - [14] S. M. Usman *et al.*, “AGM2015: Antineutrino Global Map 2015,” *Sci. Rep.* **5**, 13945 (2015).
 - [15] M. C. Gonzalez-Garcia, M. Maltoni, and T. Schwetz, “Updated fit to three neutrino mixing: status of leptonic CP violation,” *J. High Energy Phys.* **11**, 52 (2014).
 - [16] F. P. An *et al.*, “A new measurement of antineutrino oscillation with the full detector configuration at Daya Bay,” *Phys. Rev. Lett.* **115**, 111802 (2015).
 - [17] W. F. McDonough and S.-s. Sun, “The composition of the Earth,” *Chem. Geol.* **120**, 223 (1995).
 - [18] S. T. Dye, “Geo-neutrinos and the radioactive power of the Earth,” *Rev. Geophys.* **50**, RG3007 (2012).
 - [19] Y. Huang *et al.*, “A reference Earth model for the heat producing elements and associated geoneutrino flux,” *Geochem., Geophys., Geosyst.* **14**, 2003 (2013).
 - [20] <http://flask.pocoo.org/>.
 - [21] <https://www.python.org/>.
 - [22] <http://jinja.pocoo.org/>.
 - [23] <http://d3js.org/>.
 - [24] “IAEA Safeguards Glossary,” <http://www-pub.iaea.org/> (2001).
 - [25] M. Askins *et al.*, “The Physics and Nuclear Nonproliferation Goals of WATCHMAN: A Water Cherenkov Monitor for ANtineutrinos,” <http://arxiv.org/abs/1502.01132> (2015).
 - [26] R. Becker-Szendy *et al.*, “MB-3: a large water Cherenkov detector for nucleon decay and neutrino interactions,” *Nucl. Inst. Meth.* **A324**, 363 (1993).
 - [27] “A Deep Ocean Anti-Neutrino Detector near Hawaii,” <http://www.phys.hawaii.edu/~sdye/CEROS-report.pdf> (2006).
 - [28] M. Wurm *et al.*, “The next-generation liquid-scintillator neutrino observatory LENA,” *Astropart. Phys.* **35**, 46 (2012).
 - [29] B. M. Howe, “A Deep Cabled Observatory: Biology and Physics in the Abyss,” *EOS, Trans. A.G.U.* **95**, 429 (2014).
 - [30] C. G. Rothschild, M. C. Chen, and F. P. Calaprice, “Antineutrino geophysics with liquid scintillator detectors,” *Geophys. Res. Lett.* **25**, 1083 (1998).
 - [31] S. T. Dye *et al.*, “Earth radioactivity measurements with a deep ocean antineutrino observatory,” *Earth Moon Planets* **99**, 241 (2006).
 - [32] S. Enomoto *et al.*, “Neutrino geophysics with KamLAND and future prospects,” *Earth Planet. Sci. Lett.* **258**, 147 (2007).
 - [33] S. T. Dye and E. H. Guillian, “Estimating terrestrial uranium and thorium by antineutrino flux measurements,” *Proc. Nat. Acad. Sci.* **105**, 44 (2008).
 - [34] O. Sramek *et al.*, “Geophysical and geochemical constraints on geoneutrino fluxes from Earth’s mantle,” *Earth Planet. Sci. Lett.* **361**, 356 (2013).